Oscillations in Secondary to Primary Polar Crown Polarity Inversion Lines (PILs) around Solar Maximum (Smax) over Five Solar Cycles (SCs)

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NH=Northern Hemisphere
SH=Southern Hemisphere

Non-Rush Oscillations

±60°

±40°

<~20CR>

Solar minimum (Smin)

Non-Rush Oscillations

Sc20

1974

1977

1980

1983

1986

Sc21

Primaries

NH & SH

Rush-to-the-Pole (RttP)

△ RttP Ends of Secondary PILs

NH and SH Secondaries

1600

1650

1700

1750

Carrington Rotation
McIntosh Archive of 55 years of PILs (SC 19-23) and 35 years of Coronal Holes (CHs, 4/74-8/09)

Solar minimum Jul-Aug 1984

Polar coronal hole (CH) latitudinal extent ~28-30°, with low-latitude extensions

Primary PIL (polarity inversion line) 50.0°N, 40.5°S

Secondary PIL (polarity inversion line) 38.5°N, 33.5°S
PILs Can Be Close to CH Boundaries (or Extensions)  
Average Distance is 16° Apart

Polar CHs small  
(69.5cS, 60.5°N)

Chevron shapes of PILs from differential rotation (segments)

Average Distance of Primary-Secondary PILs is 14° apart
Polar CHs Disappear in Solar Maximum (end RttP SC 19)

Nearly Continuous Secondary PILs (or Polar Crown Filaments)

SC 19 from Kodaikanal (Makarov and Sivaraman, 1986 Atlas), no ARs
No CH data until Mk2 and He 10830Å in SC 20
Some hyperlong filaments (green) and lack of filaments in polar regions
Maximum Filament Locations Very Close to Maximum PIL Locations

Ave Deviation 1.2° (6°) SC 20-23, 4.3° (12°) SC 19

Maximum Filament Latitudes and Differences Between PIL and Filament Maxima
Maximum Filament Locations Similar Now to Previous Study by McIntosh (2003)

Secondary PCFs in RttP ~15° from Primary PCF and become primary after polarity change

3 RttPs in NH SC 20 (~1969-72)

Start/End latitudes ~same

Dropdown of 1st RttP ~1969 (polarity change, or 4 RttPs)

Primary-Secondary PCF ~10° start RttP and ~25° end RttP
Median PILs a Cleaner, Better Story than Filaments
(~7.5° Equatorward)

Diamonds at end RttP for Secondary PILs

Maximum Polar Crown Filaments


SC20


SC20

0 1550 1600 1650 1700
Carrington Rotation

±55°

Oscillations!

<20CR>
(Multiple) Rush-to-the-Poles (RttPs), non-Rush Periods (PILs 13-15°) and CH Boundaries (10830 Å, max 32° SC 20-22) for SC 19-23

Median Polar CH Boundaries and PILs and Differences Between Primary and Secondary PILs
The first polar CH (+) often occurs right after the last RttP primary PIL (*).
- First polar CH (+) ~1 year (11-14 CR) after polarity reversal >60°
- Persistent polar CHs (+) in the SH are 3-5 CR later, and are 7-8 CR later in the NH after the first polar CH
- The RttP end of the secondary PIL (◊) is ~22 CR past polarity change in the SH and only ~14 CR in the NH

<table>
<thead>
<tr>
<th>Median Polar CH Boundary (+) and End RttP PIL Locations</th>
<th>Polarity Reversal &gt;60° MWO SC20</th>
<th>Last Primary RttP</th>
<th>First Polar CH MK2 SC20</th>
<th>First Persistent Polar CH</th>
<th>End RttP Secondary PIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC 19 NH</td>
<td>1407 Webb84</td>
<td>1418 (11)</td>
<td></td>
<td></td>
<td>1419 (12)</td>
</tr>
<tr>
<td>SC 19 SH</td>
<td>1385-9 Webb</td>
<td>1401 (12)</td>
<td></td>
<td></td>
<td>1409 (20)</td>
</tr>
<tr>
<td>SC 20 NH</td>
<td>1525/1574</td>
<td>1575 (1)</td>
<td>1567 (-7)</td>
<td>(5) 1572 (-2)</td>
<td>(19) 1591 (17)</td>
</tr>
<tr>
<td>SC 20 SH</td>
<td>1548</td>
<td>1559 (11)</td>
<td>1560 (12)</td>
<td>(3) 1563 (15)</td>
<td>(-2) 1561 (13)</td>
</tr>
<tr>
<td>SC 21 NH</td>
<td>1691</td>
<td>1702 (11)</td>
<td>1702 (11)</td>
<td>(10) 1712 (21)</td>
<td>(-5) 1707 (16)</td>
</tr>
<tr>
<td>SC 21 SH</td>
<td>1698</td>
<td>1711 (13)</td>
<td>1712 (14)</td>
<td>(5) 1717 (19)</td>
<td>(3) 1720 (22)</td>
</tr>
<tr>
<td>SC 22 NH</td>
<td>1823</td>
<td>1835 (12)</td>
<td>1836 (13)</td>
<td>(7) 1843 (20)</td>
<td>(-6) 1837 (14)</td>
</tr>
<tr>
<td>SC 22 SH</td>
<td>1842</td>
<td>1854 (12)</td>
<td>1848 (6)</td>
<td>(9) 1857 (15)</td>
<td>(9) 1866 (24)</td>
</tr>
</tbody>
</table>

Smax Smin

Polar CH Boundaries after Polarity Reversal and RttP PIL Endings

The graph shows the median polar CH boundaries and end RttP PIL locations with corresponding data points for each solar cycle and hemisphere. The table lists the polarity reversal dates and various lags prior to and after the reversal.
Maximum PIL Locations are ~9° Poleward primary RttP slope > secondary, but not as clean
Comparison Good with Xu et al. (2018) Filaments

From Figure 3 of Xu et al. (2018) using Kanzelhöhe and Big Bear filaments (green) above 40° from Hα images where the RttP slopes are red lines. Magnetic fields are red (SH) and blue (NH) dots above 50° from Kitt Peak (1975-1995 l-o-s B so smaller), MDI/SOHO (1996-2010 radial B), and HMI/SDO (2010-2018 radial B).

Usually, RttP slopes for our study are faster for median (m) primary PIL locations than for maximum (x). Xu’s results are low or in-between. Better (faster) results with Xu et al. Kodaikanal (AGU poster).
Comparison Good with Altrock (2003, 2014)

From Figure 1 of Altrock (2014) using Fe XIV 5303Å green corona line with yearly smoothing and NH and SH added together for SC 21-23.

|       | Av NH+|SH| | Av NH+|SH| |
|-------|-------|---| | Slope °/CR | °Lat Begin/End |
| SC 21 Xu | 0.54±0.11 | 52-74 |
| SC 21 CR1666-1699 | 0.70±0.09 | 0.61±0.05 | 50-73 median | 57-78 max |
| SC 21 Altrock | 0.63 | 62-82 |
| SC 22 Xu | 0.41±0.01 | 52-70 |
| SC 22 CR1802-1830 | 0.63±0.21 | 0.46±0.18 | 51-68 median | 61-74 max |
| SC 22 Altrock | 0.85 | 57-81 |
| SC 23 Xu | 0.55±0.13 | 51-70 |
| SC 23 CR1933-1965 | 0.54±0.20 | 0.56±0.18 | 51-68 median | 58-76 max |
| SC 23 Altrock | 0.65 | 60-81 |

The RttP slopes for Altrock are in range of Xu et al. (2018) and this study, except for SC 22 where they are a bit larger. The latitudes start and end a bit higher.
Comparison Good with Hyder (1965)

From Figure 1 of Hyder (1965) using filaments from 40-80° from Meudon Hα images with estimated RttP slopes in red, with a red star in the SH with fewer observations where the median primary PIL RttP ended.

| SC 19 CR range | °/CR °lat range NH or |SH| |
|----------------|------------------------|
| NH RttP#1 Hyder | 0.89 49-73 (24/27)      |
| NH RttP#1 1367-1394 | 0.79 53-73m             |
| NH RttP#2 Hyder | 0.90 68-77 (9/10)       |
| NH RttP#2 1395-1405 | 1.25 65-77m              |
| NH RttP#3 Hyder | 1.17 63-77 (14/12)      |
| NH RttP#3 1406-1418 | 1.34 66-82m              |
| SH RttP Hyder  | 0.90 45-64 (19/21)      |
| SH RttP 1367-1388 | 1.05 45-66m              |

Slopes ~0.9°/CR from Hyder Figure 1, about same as our study.
Xu et al. ‘Migration of Polar Crown Filaments in the Past 100 Years’ (SH002-0024 Fall AGU 2020 and accepted Astrophysical Journal article 2021) uses Kodaikanal Hα images (and from BBSO and KSO later years) to find filaments and the slopes for the Rush-to-the-Poles.

- Slopes are larger than for the filaments found in Xu et al. (2018), and in better agreement with the present study.

### Table

<table>
<thead>
<tr>
<th>SC#</th>
<th>NH, SH</th>
<th>CR range</th>
<th>Lat begin/end median</th>
<th>Lat begin/end max</th>
<th>Lat/CR slope Med max Xu 2020 (2018)</th>
</tr>
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<tbody>
<tr>
<td></td>
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<tr>
<td>19 NH Xu 2020</td>
<td>1365-1406</td>
<td>53.4 to 75.8±0.5</td>
<td>59.2 to 89.4</td>
<td>0.55±0.04</td>
<td>0.51±0.09</td>
</tr>
<tr>
<td>SH</td>
<td>1365-1428late</td>
<td>-56.8 to -64.3±0.9</td>
<td>-65.1 to -75.1</td>
<td>-0.12±0.02</td>
<td>-0.88±0.04</td>
</tr>
<tr>
<td>20 NH Xu 2020</td>
<td>1502-1521early</td>
<td>50.6 to 63.9±0.7</td>
<td>58.6 to 69.1</td>
<td>0.70±0.06</td>
<td>0.29±0.06</td>
</tr>
<tr>
<td>SH</td>
<td>1509-1548early</td>
<td>-45.7 to -64.9±0.7</td>
<td>-54.9 to -70.8</td>
<td>-0.49±0.03</td>
<td>-0.39±0.08</td>
</tr>
<tr>
<td>21 NH Xu 2020</td>
<td>1660-1698</td>
<td>46.0 to 75.1±0.7</td>
<td>54.3 to 79.5±0.9</td>
<td>0.75±0.03</td>
<td>0.67±0.05</td>
</tr>
<tr>
<td>SH</td>
<td>1660-1706</td>
<td>-47.7 to -75.2±0.7</td>
<td>-55.0 to -80.6±0.9</td>
<td>-0.59±0.02</td>
<td>-0.57±0.07</td>
</tr>
<tr>
<td>22 NH Xu 2020</td>
<td>1779-1832</td>
<td>38.3 to 70.5±0.6</td>
<td>48.6 to 74.8±0.9</td>
<td>0.63±0.02</td>
<td>0.59±0.08</td>
</tr>
<tr>
<td>SH</td>
<td>1782-1851</td>
<td>-47.2 to -67.2±0.5</td>
<td>-54.6 to -81.1±0.7</td>
<td>-0.29±0.02</td>
<td>-0.57±0.07</td>
</tr>
<tr>
<td>23 NH Xu 2020</td>
<td>1930-1965</td>
<td>48.0 to 72.0±0.7</td>
<td>56.4 to 76.0±1.0</td>
<td>0.69±0.04</td>
<td>0.77±0.09</td>
</tr>
<tr>
<td>SH</td>
<td>1932-1973</td>
<td>-50.2 to -69.5±0.6</td>
<td>-59.6 to -78.8±1.0</td>
<td>-0.47±0.02</td>
<td>-0.50±0.04</td>
</tr>
</tbody>
</table>
SC 19-23 Median PIL and CH Boundary Locations
Adjusted before 3-CR Smoothing

Median Polar CH Boundaries and PILs and Differences Between Primary and Secondary PILs


Solar Latitude: -50, 0, 50

Carrington Rotation: 1400, 1450, 1500, 1550, 1600, 1650, 1700, 1750, 1800, 1850, 1900, 1950, 2000, 2050

Graph showing trends over time.
SC 19-23 Oscillations after Secondary PIL Rush-to-the-Pole End Peaks

The end of the Rush-to-the-Pole (RttP) of the secondary PIL (diamonds or triangles) is usually later than the RttP end of the primary PIL marking the polarity change at the pole at Solar maximum (Smax), red=negative and blue=positive.

Median Smoothed Polar CH Boundaries and PILs and Differences Between Primary and Secondary PILs

- Early end ~60°N in the Rush-to-the-Pole (RttP) Secondary PIL
- Smax Secondary Rush-to-the-Pole (RttP) PIL ends in Primary non-Rush PIL ~67°S
- Oscillations also in CH boundary
- Equatorward drop in latitude from South to North ~15°/CR (CR=Carrington Rotation)
Transition PILs are Secondary RttP (diamond peaks) to non-rush Primary Slopes found for full (secondary plus primary) multiple RttPs

Median 3-CR Smoothed Secondary to Primary Transition PILs

Solar Latitude

Carrington Rotation 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050
Secondary PIL Ends Its RttP \(\sim 57^\circ\text{N} \sim 58^\circ\text{S}\) in the Primary non-Rush PIL \(~3\text{ CR} \sim 9\text{ CR}\) after Solar Maximum Polarity Change

Superposed Epoch Plot with the end of the Secondary PIL’s RttP at Zero

Northern Hemisphere (NH) secondary PIL RttP end is \(~3\text{ CR}\) (1 CR median) after the Solar maximum (Smax) polarity change

Southern Hemisphere (SH) secondary PIL RttP end is \(~9\text{ CR}\) (8 CR median) after the solar maximum polarity change
~16 CR Oscillations from Solar Maximum Transition Peaks

Red lines Smax polarity change when primary PIL ends its RttP

Gold lines transition peaks or secondary PIL RttP endings

Fast Fourier Transform (FFT) Amplitudes (°Lat) and Periods (CR)
SC 23a ~5° ~35CR
SC 23b ~2° ~20+CR

SH

~10-35 CR period of oscillations

Largest SH (Southern Hemisphere) oscillations in odd SCs 19, 21, 23

Oscillations ~16 CR Smax Transition Peaks
NH amplitudes < SH except for RttP < 18 CR
Secondary PIL amplitudes > Primary PIL
~16 CR PIL Peak Period from FFT Bars and Wavelet Amplitude Sums

\[
\text{Av PIL} = \text{primary} + \text{secondary} \text{ PIL (av NH + SH)}
\]

- SH peak ~25 CR, non-Rush
- NH peak ~8 CR, RttP
- Av PIL non-Rush peak ~20 CR
~20 CR Period for CH Boundary from FFT Bars and Wavelet Sums

No major ~16 CR period because have only one CH Boundary

SH peak
~25, ~9 CR
- Similar to PIL

NH peak
~11, ~7 CR
- Similar to PIL
~15°/CR Disturbance Expands Polar Coronal Holes ~50% from South to North in 2005 CR2023-35

Southern PIL wavelets ~30 CR before, ~22 CR after and smaller amplitudes

From Howe (2016) meridional flows and 5 G unsigned magnetic flux. Overplot SC 23 PILs and Coronal Hole boundaries.
CONCLUSIONS

The RttP End of the Secondary PIL in the Transition to the non-rush Primary PIL

Other periods shared with Coronal Hole (CH) boundaries of ~25 (SH), ~20 (non-rush), ~7-12 CR (mostly NH)

DISTINCT ~15°/CR Disturbance from Southern Hemisphere (SH) to Northern Hemisphere (NH) in 2005 SC 23 solar minimum!

What do modelers think happened here?

What solar interior explains B, CHs, and RttP PILs in Smax?

https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps

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Figure 14 from Muñoz-Jaramillo et al. (2018) from facular counts and used from 1955-1968 in slide 9 (times 3), but is ~3 times smaller than polar field of Y-M Wang in slide 9, and ~3 times smaller than MDI and HMI radial fields in slide 11. KSO LOS (line-of-sight) field in slide 11 is (naturally) smaller in SC 21-22, unlike this proxy field or the polar field of Y-M Wang from MWO and WSO, which shows the smallest magnitudes in SC23 at the end.